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Bringing the Fuzzy Front End into Focus

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Introduction

Technology planning is relatively straightforward for well-established research and development (R&D) areas — those areas in which an organization has a history, the competitors are well understood, and the organization clearly knows where it is going with that technology. What we are calling the "fuzzy front-end" in this paper is that condition in which these factors are not well understood — such as for new corporate thrusts or emerging areas where the applications are embryonic. While strategic business planning exercises are generally good at identifying technology areas that are key to future success, they often lack substance in answering questions like:

1. Where are we now with respect to these key technologies? ... with respect to our competitors?
2. Where do we want or need to be? ... by when?
3. What is the best way to get there?

In response to its own needs in answering such questions, Sandia National Laboratories is developing and implementing several planning tools. These tools include knowledge mapping (or visualization), PROSPERITY GAMES and technology roadmapping — all three of which are the subject of this paper.

Knowledge mapping utilizes computer-based tools to help answer Question 1 by graphically representing the knowledge landscape that we populate as compared with other corporate and government entities. The knowledge landscape explored in this way can be based on any one of a number of information sets such as citation or patent databases.

PROSPERITY GAMES are high-level interactive simulations, similar to seminar war games, which help address Question 2 by allowing us to explore consequences of various optional goals and strategies with all of the relevant stakeholders in a risk-free environment.

Technology roadmapping is a strategic planning process that helps answer Question 3 by collaboratively identifying product and process performance targets and obstacles, and the technology alternatives available to reach those targets.

Knowledge Mapping

Why Knowledge Mapping

Knowledge has always been of paramount importance in decision-making processes in research and development. As the amount and availability of information have increased dramatically in recent years, synthesis of information to gain knowledge using traditional methods has become increasingly more difficult. This difficulty has created a surging interest in and use of data mining and knowledge management tools. Yet, while these tools have helped in a statistical fashion, few if any reveal the implicit structure of a large dataset in a way that is intuitive to the analyst.

To overcome these shortfalls, researchers have searched for methods to present data in a manner that takes advantage of the human capability to process large amounts of information visually. A number of research efforts and commercial ventures have written software to address this issue. For instance, the VISUAL INSIGHTS project from Lucent Technologies [1] and the SPIRE project originated at Pacific Northwest National Laboratory [2] are two that have much in common with our approach. However, we are not aware of any other tool for visualizing large datasets that has the interactivity and flexibility of VxInsight.

What is Knowledge Mapping?

VxInsight is a knowledge visualization tool developed by Sandia National Laboratories [3] to aid in answering the question "Where do we put the next research dollar for the most impact?" It can provide information to allow us to answer the first question above: "Where are we now with respect to our key technologies, and with respect to our competitors?"

VxInsight provides a graphical interface to very

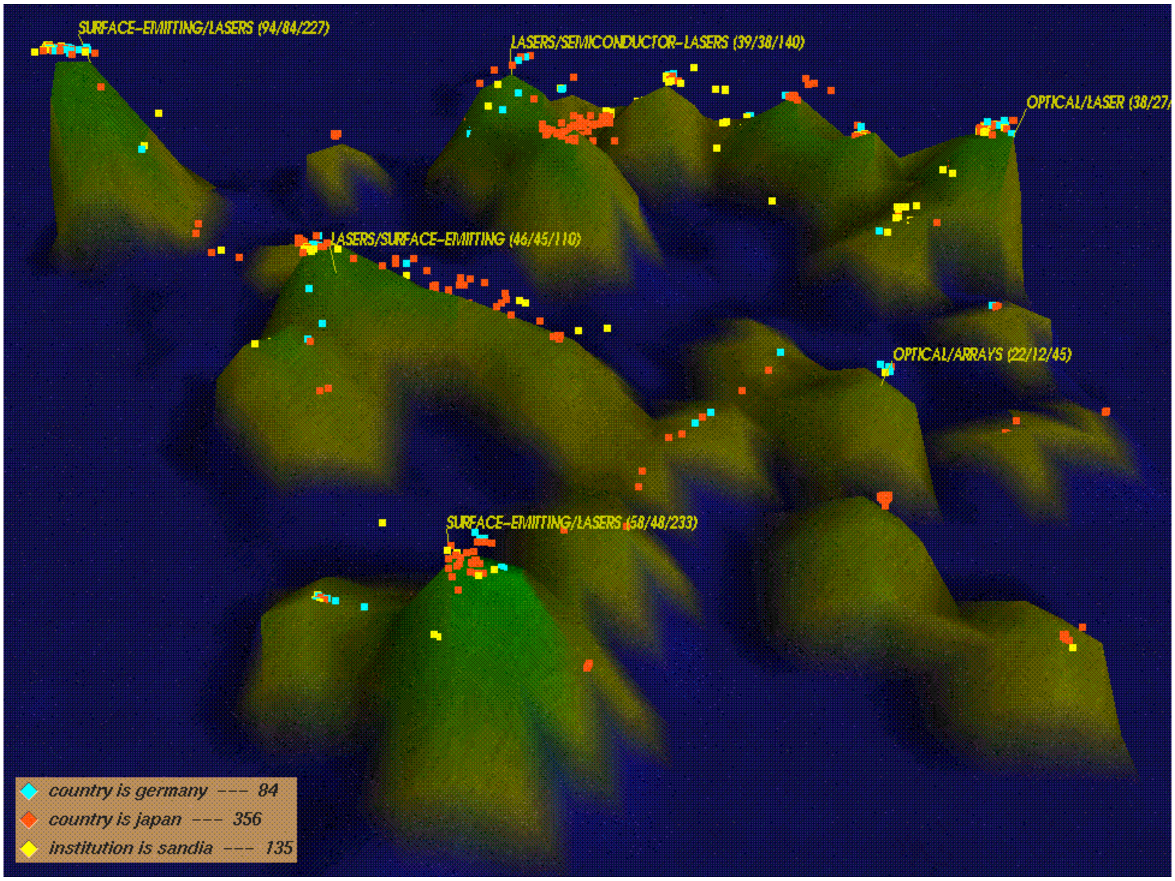

Figure 1. Query ability of VxInsight applied to a vertical cavity surface-emitting lasers (VCSELS) database.

large datasets, displaying data as a 3-D virtual landscape in which the height of a mountain reflects the density of data elements beneath it. This terrain-based representation, with data elements grouped by similarity, enables the human analyst to visualize implicit structure in the data, and to discover relationships among data elements and groups. VxInsight combines the power of SQL queries to a relational database with graphical interactivity that allows the analyst to examine the data at multiple scales.

VxInsight has been designed to work with a broad class of data. Any database for which a similarity relationship between elements can be defined is suitable for visualization. For our purposes, we have worked most extensively with a portion of the Science Citation Index (SCI), a database of scientific papers and their citation links available from the Institute for Scientific Information (ISI).

VxInsight has many features that aid the analyst in navigation and visualization in keeping with current graphical user interface (GUI) design principles. For example: a "mouse" controls the current view through zooming and rotation; labels for the most significant peaks in the current view are generated; different landscape rendering schemes are available; connection networks such as the citation of one paper by another can be displayed as arrows drawn from one object to the other; and a range-slider function allows the temporal growth, or ebb and flow, of different clusters of data to be explored.

VxInsight also has the ability to query a database and highlight the matching data elements on the terrain (see Figure 1). Many different queries can be displayed simultaneously using different highlight colors. For instance, several queries could light up the papers authored at Sandia, and in Japan and Germany. The analyst could then visually see (by reference to peak labels and areas of color concentration) technical areas in which a particular country or company might be dominant.

In summary, VxInsight is a powerful and flexible tool to allow the analyst to explore and glean knowledge from large datasets.

Knowledge Mapping examples

Methodology

The use of VxInsight goes through several steps leading up to exploration of the data. First, the analyst must identify the desired database for study. For

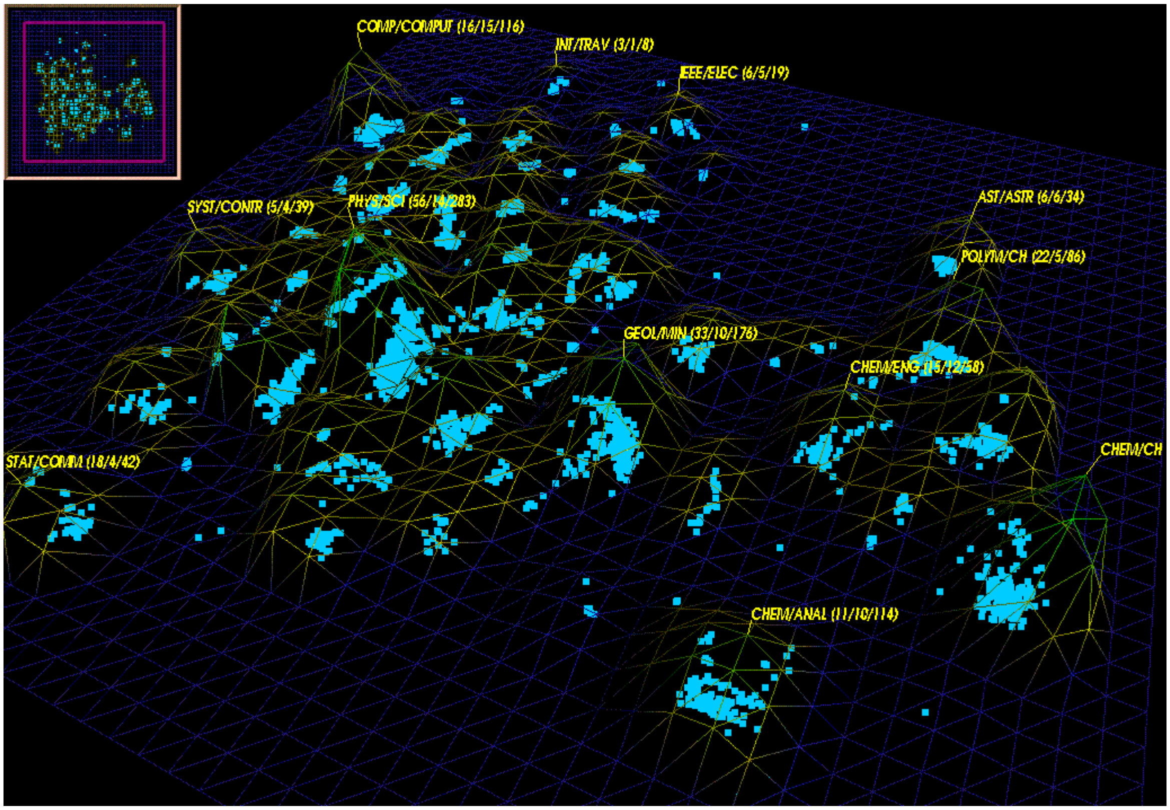

Figure 2. Illustration of data clustering in VxInsight (mesh terrain displayed).

example, although the SCI contains nearly 5 million articles, an analyst may only be interested in information related to a particular technology. Traditional methods, such as SQL queries based on keywords, categories, common references, etc., may be used to select the appropriate subset of the larger dataset.

Second, a similarity function between data elements must be defined. This is a critical step to the process in that VxInsight clusters elements by their similarity. A large similarity value implies that two objects are very similar, and thus should be close to one another on the map. Very small or zero similarity values imply that two objects should be far apart. The similarity function can be based on many things including: common keywords, identical vocabulary, direct links in web documents, citation links in scientific papers or patents, transaction links between entities, common status or membership of individuals, etc. For the SCI data, similarity is based on multiple generations of citation links.

Third, the data elements must be placed geometrically on an x,y plane, a step known as ordination. VxInsight has two choices of ordination algorithms: an eigenvector solution, and a force-directed placement solution. Each uses the similarity measure defined above as input. The eigenvector solution has the advantage of finding the optimum mathematical positions for the data elements. However, these solutions tend to form one large cluster, which does not lend itself well to interactive visualization. The force-directed placement algorithm allows data elements to move under attractive (similarity-based) and repulsive (grid-based) forces that produce attractive visualizations. However, these solutions do not produce a mathematically optimum ordination. In our estimation, a combination of the two approaches promises to work better than either one alone. The eigenvector algorithm is run first to get a mathematically robust solution, and then the force-directed placement routine is run, allowing the large cluster to relax into many clusters (see Figure 2). Once the ordination is completed, the landscape can be generated and explore in VxInsight.

Current Applications

We have applied VxInsight in several ways to enhance R&D and potential strategic partnering. VxInsight has helped Sandia to: (1) make decisions about where to invest discretionary R&D monies; (2) identify potential strategic partners by having knowledge of relative technical emphases of companies and universities; and (3) explore partnerships based on the development and use of the tool itself.

One of the first datasets visualized with VxInsight

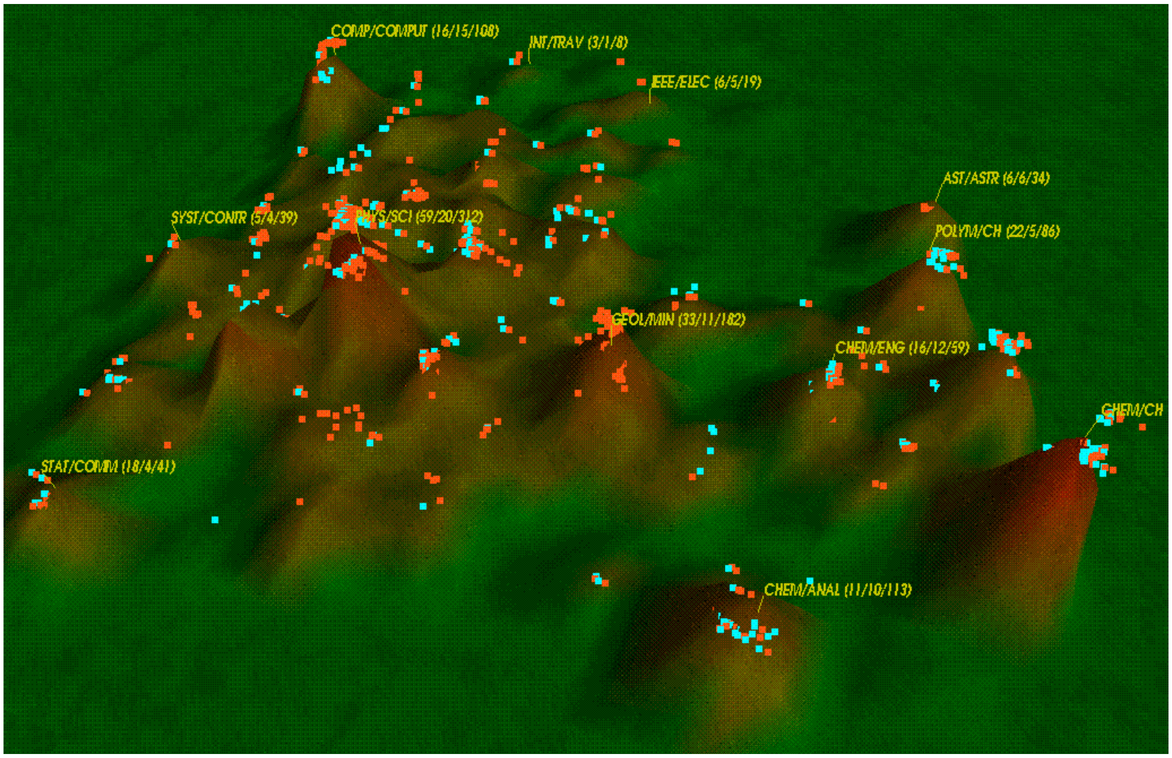

Figure 3. Comparison of two institutions on a "map of science."

was a set of 2000 papers comprising vertical cavity surface-emitting lasers (VCSELS) and related technologies (see Figure 1), an area in which Sandia has made significant advances. Visual exploration of this dataset reveals those particular technologies in which Sandia has great strength with little outside competition. It also reveals other related areas in which Japanese and German institutions have significant strengths and in which it would be less beneficial for us to invest in new research.

Another use of VxInsight involves the generation of institutional profiles based on publication data. A map of the physical sciences was created based on journal-to-journal citations. Journals with similar content clustered together, with each cluster representing a technical field (e.g. physical chemistry, solid state physics, fluid dynamics, statistics, etc.) A qualitative comparison of two institutions (companies, universities, government labs) can be made by highlighting the journals in which each institution publishes. Figure 3 shows that company BLUE has more activity on the right-hand side of the map, in the chemistry-related areas, while company ORANGE is more centered in the physics, materials, and geology areas to the middle and left of the map. Quantitative comparisons can also be made using traditional database methods by counting the number of papers each institution has published in each cluster. Sandia has used comparisons such as these to profile the relative emphases placed on each technical area by current and potential future partners. This provides not only competitive intelligence, but useful information in pursuing new partnerships.

Finally, Sandia partners with other institutions in further development of the VxInsight tool. In some cases this work is to tailor the tool to the needs of a particular application, while in others it is to explore new databases of common interest. This may enable such efforts as patent trend analysis, transactions analysis, and detection of fraud.

PROSPERITY GAMES

While knowledge mapping gives us information to understand where we are right now, it does not answer the second question "Where do we want or need to be, and by when?" The PROSPERITY GAMES process has been designed to help answer this question.

What are PROSPERITY GAMES

PROSPERITY GAMES are free-form simulation games designed to facilitate multi-dimensional examination of strategic, political, ethical, and social issues. They are called games in that the activities involved are structured around a set of rules, players, goals, and objectives, along with the concepts of competition and cooperation. They are simulations in that certain aspects of reality are incorporated into the game as simplified models. They are described as being free-form in nature because move assessments are typically related to a textual description of a mix of economic, political, and other factors, rather than by the use of prepared formulas or algorithms as are common in a traditional war game.

The essentials for the conduct of a PROSPERITY GAME are: a group to prepare, organize, and control the game; players organized in teams to represent the different stakeholders; a suitable facility in which these groups can conduct their deliberations; and some means of communicating among the groups. A typical PROSPERITY GAME has ten playing teams and a control team. Each playing team usually has six to eight players, a facilitator, and an observer/analyst. The players must be carefully selected as their knowledge about the topic being simulated is the sine qua none of a useful game.

The game is initiated after the teams are presented with a scenario describing the situation they face. Generally, game time begins in the present and extends over the next five or ten years. Game play proceeds in an open environment. PROSPERITY GAMES feature the processes of planning and negotiation. Players control the content of the games and generate their own strategies and goals or objectives, and implement them through expenditure of resources and partnering. The game evolves as the control group uses the playing teams' moves to develop and present new problem situations. A final debriefing allows the teams to share their experiences.

What are PROSPERITY GAMES good for?

In governmental affairs, gaming has enjoyed widespread support as a tool for addressing military, economic and diplomatic issues. Within the corporate arena, however, gaming is one tool that is often neglected, perhaps because it is poorly understood and because of misplaced expectations. Gaming is not an end unto itself. It is one tool that can be brought to bear to solve certain operational issues. It should always be used in support of other tools such as process models, scenario writing, group judgement techniques, and formal planning. In contrast to these other techniques, gaming has some particular strengths that make it attractive for addressing certain problems, as outlined below.

- Games and simulations are characterized by greater participation and involvement than other approaches (e.g., seminar-style workshops). The increased participation generally translates to improved “brainstorming” and planning, better measures of group opinions and judgement, and improved advocacy in real life for such things as institutional goals (whether they changed or not in the course of the game). Along the same line, gaming is a way to socialize new programs and quickly build teams out of diverse groups.
- Gaming encourages “out-of-the-box” thinking, imagination, and innovation. Many people view games egocentrically, and play with a focus on their own position. However, the most successful players — in keeping with game theory — take an allocentric viewpoint. Anticipating a future state and reasoning backward to today's needed actions requires an understanding of the other players and what you can bring to them. The needed actions should be geared toward “changing the game” to increase your added value and to create win-win strategies.
- Free-form gaming is useful for exploring complex relationships and problems that may pose significant challenges to more traditional analytical methods. During play, discovery is emphasized and highly valued. The principal issues are generally quickly identified and put out “on the table” for discussion. The particularly important, but generally poorly understood, topics and questions so identified can then be addressed in other forums for further study and resolution.
- Gaming explores generally unquantifiable phenomena such as the human dimension. This may range from something as simple as observing behavior under the conditions imposed by the simulation, to the more complex profiling of competitive team behavior under the conditions of imperfect intelligence. Decision makers and managers who are playing may be more interested in the personal styles of their bureaucratic and political colleagues and competitors in a game setting than they are in the actual game or its outcomes.
- Teaming, “networking” and making new contacts are manifest, if nebulous, outcomes of every game that continues into real life.
- A classic problem that sometimes surfaces early in a game is the existence of leadership schisms and the lack of consensus on an organization's purpose, vision, and goals. These differences will often be revealed; successful engagement in the game will require agreement to be reached and strategies and contingency plans to be developed on the basis of this agreement.
- The limited resources in play during a game, both in terms of game “dollars” and time, and often in terms of reward and penalty, provide a means to identify and gauge priorities.
- Games are important educational experiences.

PROSPERITY GAME examples

Each PROSPERITY GAME is designed to fulfill a set of objectives. In general, several of the objectives will be in line with the "why game?" points outlined above, including:

- Develop relationships and partnerships among industry, government, national labs, and academia.
- Develop an understanding of the roles and relationships of, and the interactions among, these four groups.

Fulfilling such objectives can be very useful, but the results are very tenuous and difficult to capture. Rather, the examples below discuss more specific outcomes. However, it should always be kept in mind that these other types of benefits accrue as well.

PROSPERITY GAMES as a Technology Roadmap Foundation

Sandia's historic role in creating and designing the major portions of the nation's stockpile of nuclear weapons and our ongoing responsibility for system safety, security, and control for these weapon systems has, of necessity, resulted in a significant investment in electronics technology. The results have not only fulfilled mission requirements, but have made major impacts in industry as well. Notable achievements are many, and include the invention of the laminar airflow clean room, advances in radiation-hardened circuits, extreme ultraviolet lithography, and integrated microelectronics/microelectromechanical systems technology. But this has not taken place in a vacuum; Sandia has always worked closely with the U.S. electronics industry and related associations in many ways. One result stemming out of this real, if often only loosely defined, set of relationships was that Sandia and the Center for National Industrial Alliances worked with the Electronics Industry Association (EIA), the American Electronics Association (AEA), the Electronics Subcommittee (ESC) of the Civilian Industrial Technology Committee of the National Science and Technology Council (NSTC), and the Ideas in Science and Electronics (ISE) 16th annual Electronics Exposition and Symposium to conduct a series of four PROSPERITY GAMES in 1994. Specific objectives for these games included [4]:

- Explore a long-term (10-20 year) time horizon in thinking about crafting technology strategies and policies.
- Stimulate thinking in a focused and directed fashion to help develop new insights regarding future technology strategies and policies.
- Lay the foundation for a roadmap to economic competitiveness in the electronics industry.

The tangible outcome: since many of the players were members of the National Electronics Manufacturing Initiative (NEMI), ideas that were developed during the games eventually had influence on the "Electronics Manufacturing Technology Roadmaps -and- Options for Government Action" that was released later that year.

The experience gained in using games in supporting the NEMI roadmap development was called on again in 1995 when, in an effort sponsored by the Defense Advanced Research Projects Agency and The Koop Foundation, Sandia conducted a game in biomedical technology. Materials developed during the game were later used as input for developing a biomedical technology roadmap.

Prosperity Games™ as an impetus for action

During the years of 1995, 1996 and 1997, Sandia conducted a series of games under such titles as: ... Prosperity-Diversity Game ..., Future@Labs.PROSPERITY GAME, and Industrial Partnership PROSPERITY GAME. Sponsors for these games included: the Industry Advisory Boards of the DOE national labs; the DOE national labs; Lockheed Martin Corporation; and the University of California. Although details varied from game to game, the objectives embraced the overarching concept of:

> Explore options for synergism, increased collaboration and partnerships among government, laboratories, universities, and industry that enhance the DOE laboratories' abilities to meet national missions and needs.

Whether these games served as the kernel or simply solidified preexisting ideas, they did serve as the impetus for a number of far reaching activities. The more dramatic include:

- Formation of the National Coalition for Research and Development (NCRD), whose mission is: "Industry, university, and federal laboratory alliances: Optimizing the nation's R&D"
- National R&D summits organized by the Council on Competitiveness, the most recent of which was the National Innovation Summit held at Massachusetts Institute of Technology in March, 1998.
- Congressional staffers developed ideas in play during the game as legislation that eventually ended up for consideration before the U.S. Congress.
- Sandia reorganized business planning, partnerships, licensing, and agreements activities, and improved related processes.

It should be noted that none of these activities were planned outcomes for the games, but that the environment of the games fostered “out-of-the-box” thinking, imagination, and innovation, and garnered advocacy for the resultant ideas. Nor are such results restricted to this set of games.

Technology Roadmapping

Although PROSPERITY GAMES help us understand what we want the state of our key technology areas to be at some point in the future (e.g. 5 years), we need to answer the third question “What is the best way to get there?” Technology roadmapping is a powerful process to map the detailed steps needed for us to accomplish our goals.

What are Technology Roadmaps?

Technology roadmapping is a form of technology planning. It is a process whereby a framework can be developed to organize and present critical technology-planning information in a way that improves technology investment decisions. Technology roadmapping can be conducted for different scopes—industry or corporate—and from different technology perspectives—emerging and product. Successful technology roadmapping efforts are based on a synthesis and integration of the work of a team of experts in the particular field of interest. A technology roadmap is the document that is generated by the technology roadmapping process.

The emerging technology roadmap focuses on a single technology, describes the way it is expected to develop, and may include project plans to support that development. It focuses on: (1) forecasting the development and commercialization of a new or emerging technology; (2) the competitive position of a company with respect to that technology; and (3) how the emerging technology and the company’s competitive position will develop. The result of an emerging technology roadmap may be a decision to allocate additional resources to develop the technology to improve your competitive position. The implication is that as the technology develops, uses will be found for it [5]. In contrast, rather than looking for a need that can be satisfied by a particular widget, product technology roadmapping is driven by critical product (or process) needs. The product technology roadmap identifies, as a function of these needs: (1) critical supporting technology areas and their drivers; (2) technology gaps that must be filled to meet targets; (3) the technology alternatives and information needed to make trade-off decisions; (4) and a plan to develop and deploy appropriate technology alternatives. Emerging technology roadmaps may even be used to form subsections of complex product maps. The plan set forth in a roadmap includes development time frames and milestones, and often identifies ways to leverage R&D investments through coordinating research activities. In effect, a technology roadmap identifies alternate technology “roads” for meeting certain product or process objectives. A single path may be selected and a plan developed. If there is high uncertainty or risk, then multiple paths may be selected and pursued concurrently.

Some companies have effectively combined the characteristics of both types of technology roadmaps. Both should be integrated with other business planning techniques.

What are Technology Roadmaps good for?

Technology planning is important for many reasons. There is increased competition. Products are becoming more complicated and customized. Product time-to-market is shrinking. Product life is shortening due to obsolescence. Investment strategies are looking for short-term payoffs, thus reducing R&D funding. These problems and more require companies to remain focused and understand both their competitors and their markets. If such problems are to be met, there must also be a linkage between a company’s technology investment decisions and its business requirements. Technology roadmapping is an effective tool for providing this linkage.

As a specific technique for technology planning at the strategic level, the main benefit of roadmapping is the way in which it organizes information to support technology investment decisions. In particular, since product roadmaps are linked to objectives, they can help focus and leverage R&D resources on the critical technologies that are needed to meet those objectives. Roadmapping is especially useful when the technology investment decisions are not straightforward, such as when it is not clear which alternative to pursue (e.g., enhance an existing technology or replace it with a new technology), how quickly the technology is needed, or when there is a need to coordinate the development of multiple technologies (e.g., across multiple projects or when dealing with technologies that are related to a corporation’s core competencies).

Other uses of technology roadmapping include: (1) helping to develop a consensus about a set of needs and the technologies required to satisfy those needs; (2) providing a mechanism to help experts forecast technology developments in targeted areas; and (3) providing a framework to help plan and coordinate technology developments within a company, or even, by focusing on common needs, show how an entire industry can more effectively address critical research and collaboratively develop common technologies. This latter use often arises when it is recognized that the technologies that need to be developed are too expensive or risky for a single corporation to develop independently. It can also identify underfunded or unfunded but important technologies.

Technology Roadmap examples

Methodology [6]

Although there may be as many variations in roadmapping techniques as there are organizations using them, successful roadmapping can be described by a small set of phases and steps.

The first, and perhaps most critical, phase requires the key decision makers to: (1) perceive that they have a problem that a technology roadmap can help solve; (2) decide specifically what will be roadmapped and how the result will help them make their investment decisions; (3) accept, buy into, and use the results; and (4) provide the resources needed to create the roadmap.

The second phase utilizes the inputs of technical experts to actually generate a roadmap. The steps are to: (1) identify and agree on the product definition (e.g., an energy-efficient vehicle); (2) identify the critical system requirements and targets which provide the overall framework for the roadmap and are the high-level dimensions to which the technologies relate (e.g., fuel consumption with performance targets of 60 miles per gallon (mpg) by 2000 and 80 mpg by 2005); (3) specify the major technology areas that can help achieve the critical system requirements for the product (e.g., materials, engine controls, and sensors); (4) transform the critical system requirements into technology-oriented drivers for the specific technology areas (e.g., specify vehicle weight or maximum engine temperature); (5) identify technology alternatives and their time lines (e.g., advanced composites); (6) develop recommendations for the technology alternatives that should be pursued based on trade-offs like cost, schedule, and performance within the context of a broad perspective (e.g., critical paths, competitive advantage, and so called "disruptive" technologies [7]); and (7), document the results in the roadmap.

The final phase involves engendering actual acceptance and support for the roadmap. This might include: (1) critiquing and validation; (2) developing an implementation plan; and (3) providing periodic reviews and updates. The review and update cycle allows both the roadmap and the implementation plan to be adjusted for changes in the needs and the technologies.

The National Electronics Manufacturing Initiative (NEMI) Technology Roadmap

One example of an industry-level technology product roadmap that Sandia has been involved in is the National Electronics Manufacturing Initiative (NEMI) Technology Roadmap [8], which was developed to address common requirements for electronics manufacturing technology.

Although the industry members of the association compete on semiconductor and electronics designs and the products that use them, they all generally use the same underlying manufacturing technology. This provided a common area on which the industry could cooperate, and is the focus of the roadmap.

Roadmaps were completed in several categories including electronic interconnection substrates, photonics manufacturing, board assembly, and precision electromechanical assembly. In the board assembly area, critical system requirements included flexible chip placement capacity per square foot, IC placement accuracy, PCMCIA conversion cost per pin, and IC lead pitch. Targets/drivers for each of these critical system requirements were identified for the 3-5 year and 5-15 year time frames. With system requirements and their accompanying targets identified, more detail was added to the roadmap. The board assembly area was further refined to include several subcategories, one of which was PCMCIA. Key manufacturing processes were identified for the PCMCIA subcategory, two of which were component and IC attach technologies. Solder was the current technology used for these processes (in 1994). Anisotropic conductive adhesives and films were identified as the preferred technologies in the 3-5 year time frame to meet the critical system requirements in the board assembly / PCMCIA area. The NEMI roadmap is actively critiqued and updated every two years.

Tool Integration and Synergy

While often used "on their own" to meet a specific technology planning need, knowledge mapping, Prosperity Games, and technology roadmapping can also be used with a great degree of synergy. The three tools can be thought of as a sideways figure-8 where Prosperity Games and technology roadmapping are at the two ends, and knowledge mapping is at the intersection of the two loops, as shown in Figure 4. An earlier model had the three tools as the three points on a triangle, but our experience has shown that the interface between PROSPERITY GAMES and roadmapping is strengthened by the knowledge gained from knowledge mapping. Thus, the model has been condensed to place knowledge mapping as the central link for our technology planning needs.

The links between knowledge mapping and PROSPERITY GAMES can be thought of in terms of pre-game and post-game interfaces. Knowledge

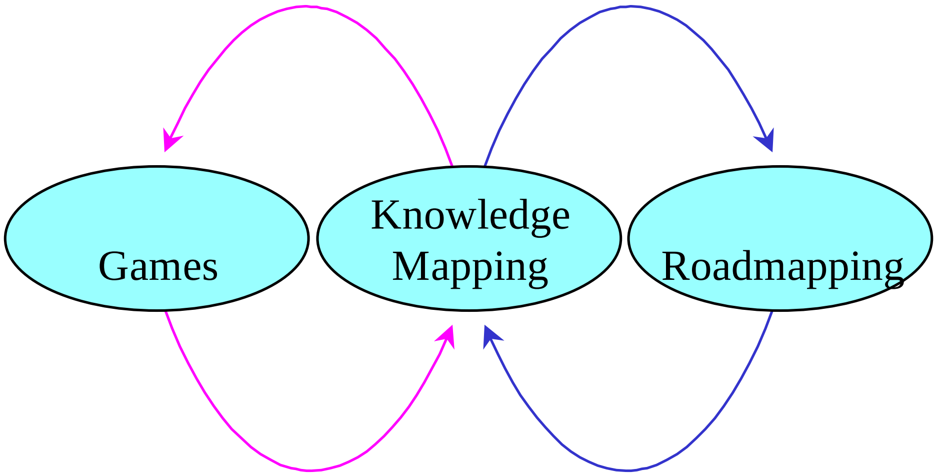

Figure 4. Links between partnership development tools.

mapping is used pre-game to develop a map based on the desired focus of a PROSPERITY GAME. This map can then be navigated and queried to show the main technical areas with their relative priorities, providing useful background information for the game. Another key use is to provide a first-cut list of the companies or individuals who should be represented at the game. The post-game knowledge map is used to examine specific areas in which the results of the game did not follow the expected path. Do the data justify the choices made by players during the game? Do the game choices represent next-steps, leap-frogs, or quantum changes in technology? Forecasting based on the analyst's synthesis of game results with map information can also be done.

The links between knowledge mapping and technology roadmapping are similar to those mentioned above for PROSPERITY GAMES. The primary purpose of the pre-roadmap knowledge map is to provide the appropriate background information for the roadmapping exercise, including a list of those who should participate. Like the post-game knowledge map, the post-roadmap knowledge map is also an analysis tool. However, its primary function is to monitor progress. The results of implementation of the roadmap should be evident in a knowledge map prepared after sufficient time has passed. Assuming that the knowledge map contains the most recent information, technical progress can be monitored. Where is work moving according to schedule? Where is it behind? Will the desired technologies be available at the desired time based on the trend shown in the map? Are our competitors making faster progress? Is there a related field where breakthrough work is taking place that might impact the field of interest? These are all questions that can be explored with the help of the knowledge map.

To illustrate the use of a knowledge map to monitor roadmap progress, let us revisit the roadmapping example used previously, the 1994 NEMI roadmap. To create this knowledge map, a core set of technical papers was gathered by querying the ISI database for terms matching many technical terms from the 1994 NEMI roadmap. The set of papers was then extended by adding two generations of citing and cited links from these core papers, to create a dataset of over 28,000 papers. Figure 5 shows this map, with one area of interest from the roadmap highlighted. For instance, anisotropic conductive adhesives were listed in the PCMCIA board assembly category of the roadmap as the preferred component and IC attach technologies for the 3-5 year time frame. Figure 5 shows the new (1995-96) work in that area. However, only one US company is publishing in the area. Thus, it is uncertain if the technology will be mature as soon as desired. Many other monitoring examples could be shown with this figure as well.

Summary

Technology planning tools are being developed and used at Sandia National Laboratories to meet the challenge of the fuzzy front end of R&D. Knowledge mapping helps to answer the questions of "Where are we now with respect to our key technologies? ... who are our competitors? ... where are they?" With the knowledge gained from insightful mapping, a PROSPERITY GAME can provide insights into "Where do we want to be, and by when?" A knowledge map can then be used to analyze the game results and prepare detailed information for a technology roadmapping exercise, which adds the detailed plan of

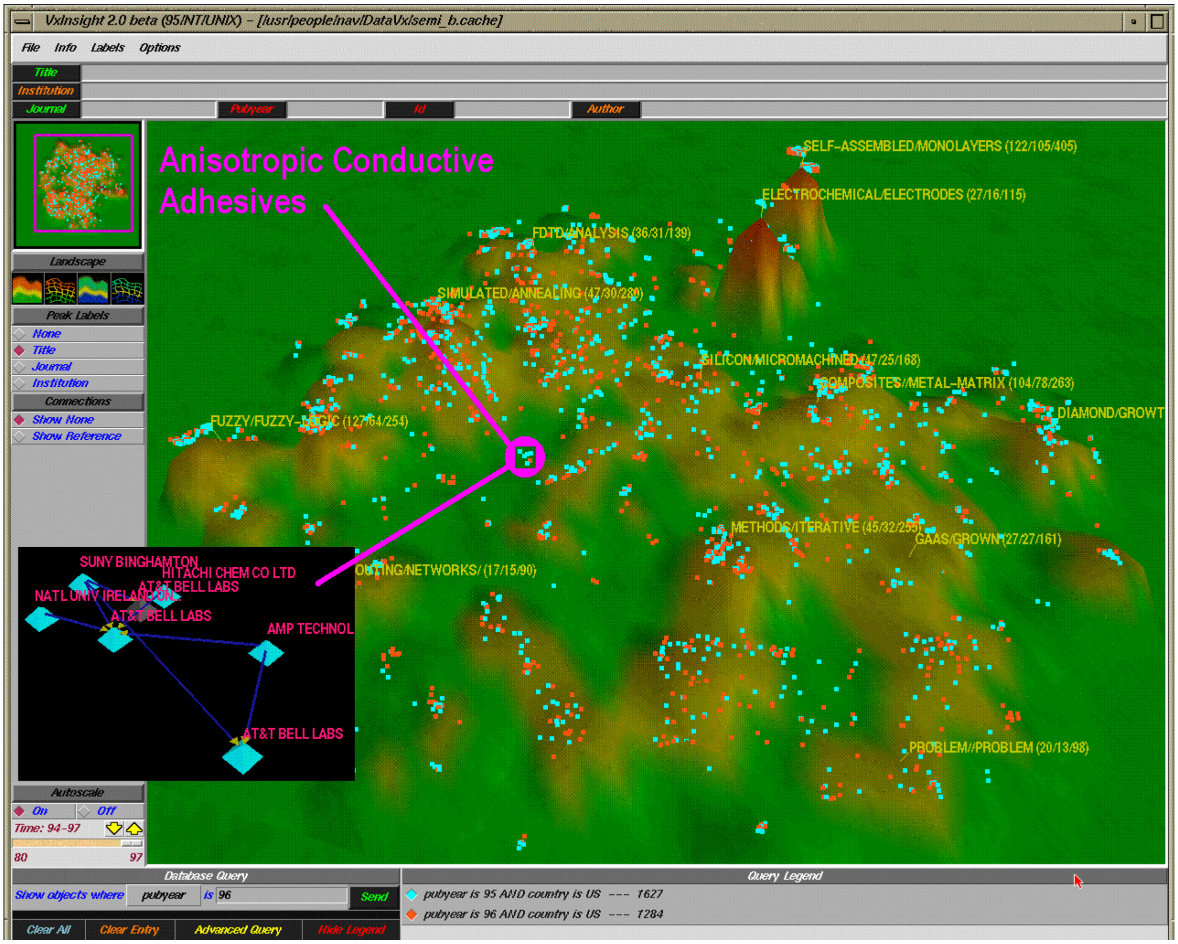

Figure 5. Using VxInsight to monitor technology roadmapping progress.

"How should we get there?" The knowledge map can also provide input to answer the questions of "Can we get there in time by ourselves? ... or should we partner? ... and with whom?" By such means, these tools, when properly applied, can aid in making robust R&D decisions.

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